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Transmission Line Parameters

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The power transmission line is one of the major components of an electric power system. Its major function is to transport electric energy, with minimal losses, from the power sources to the load centers, usually separated by long distances. The design of a transmission line depends on four electrical parameters:

1. Series resistance
2. Series inductance
3. Shunt capacitance
4. Shunt conductance

The series resistance relies basically on the physical composition of the conductor at a given temperature. The series inductance and shunt capacitance are produced by the presence of magnetic and electric fields around the conductors, and depend on their geometrical arrangement. The shunt conductance is due to leakage currents flowing across insulators and air. As leakage current is considerably small compared to nominal current, it is usually neglected, and therefore, shunt conductance is normally not considered for the transmission line modeling.

13.1 Equivalent Circuit

Once evaluated, the line parameters are used to model the transmission line and to perform design calculations. The arrangement of the parameters (equivalent circuit model) representing the line depends upon the length of the line.

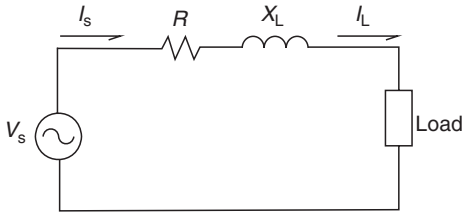


FIGURE 13.1 Equivalent circuit of a short-length transmission line.

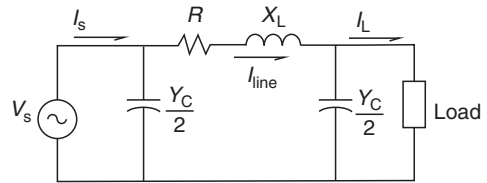


FIGURE 13.2 Equivalent circuit of a medium-length transmission line.

A transmission line is defined as a short-length line if its length is less than 80 km (50 miles). In this case, the shunt capacitance effect is negligible and only the resistance and inductive reactance are considered. Assuming balanced conditions, the line can be represented by the equivalent circuit of a single phase with resistance R , and inductive reactance X_L in series (series impedance), as shown in Fig. 13.1. If the transmission line has a length between 80 km (50 miles) and 240 km (150 miles), the line is considered a medium-length line and its single-phase equivalent circuit can be represented in a nominal π circuit configuration [1]. The shunt capacitance of the line is divided into two equal parts, each placed at the sending and receiving ends of the line. Figure 13.2 shows the equivalent circuit for a medium-length line.

Both short- and medium-length transmission lines use approximated lumped-parameter models. However, if the line is larger than 240 km, the model must consider parameters uniformly distributed along the line. The appropriate series impedance and shunt capacitance are found by solving the corresponding differential equations, where voltages and currents are described as a function of distance and time. Figure 13.3 shows the equivalent circuit for a long line.

The calculation of the three basic transmission line parameters is presented in the following sections [1–7].

13.2 Resistance

The AC resistance of a conductor in a transmission line is based on the calculation of its DC resistance. If DC current is flowing along a round cylindrical conductor, the current is uniformly distributed over its cross-section area and its DC resistance is evaluated by

$$R_{DC} = \frac{\rho l}{A} \quad (\Omega) \quad (13.1)$$

where ρ = conductor resistivity at a given temperature ($\Omega\cdot\text{m}$)

l = conductor length (m)

A = conductor cross-section area (m^2)

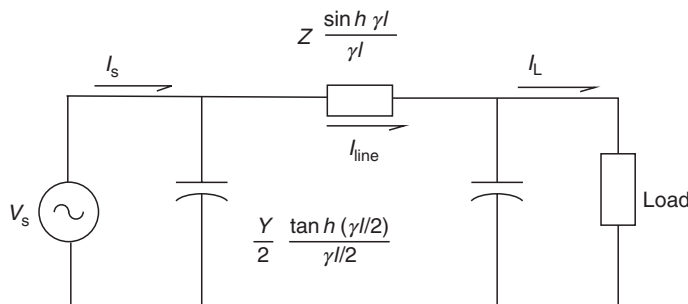


FIGURE 13.3 Equivalent circuit of a long-length transmission line. $Z = z l$ = equivalent total series impedance (Ω), $Y = y l$ = equivalent total shunt admittance (S), z = series impedance per unit length (Ω/m), y = shunt admittance per unit length (S/m), $\gamma = \sqrt{ZY}$ = propagation constant.

If AC current is flowing, rather than DC current, the conductor effective resistance is higher due to frequency or skin effect.

13.2.1 Frequency Effect

The frequency of the AC voltage produces a second effect on the conductor resistance due to the nonuniform distribution of the current. This phenomenon is known as skin effect. As frequency increases, the current tends to go toward the surface of the conductor and the current density decreases at the center. Skin effect reduces the effective cross-section area used by the current, and thus, the effective resistance increases. Also, although in small amount, a further resistance increase occurs when other current-carrying conductors are present in the immediate vicinity. A skin correction factor k , obtained by differential equations and Bessel functions, is considered to reevaluate the AC resistance. For 60 Hz, k is estimated around 1.02

$$R_{AC} = R_{AC}k \quad (13.2)$$

Other variations in resistance are caused by

- Temperature
- Spiraling of stranded conductors
- Bundle conductors arrangement

13.2.2 Temperature Effect

The resistivity of any conductive material varies linearly over an operating temperature, and therefore, the resistance of any conductor suffers the same variations. As temperature rises, the conductor resistance increases linearly, over normal operating temperatures, according to the following equation:

$$R_2 = R_1 \left(\frac{T + t_2}{T + t_1} \right) \quad (13.3)$$

where R_2 = resistance at second temperature t_2

R_1 = resistance at initial temperature t_1

T = temperature coefficient for the particular material ($^{\circ}\text{C}$)

Resistivity (ρ) and temperature coefficient (T) constants depend upon the particular conductor material. Table 13.1 lists resistivity and temperature coefficients of some typical conductor materials [3].

13.2.3 Spiraling and Bundle Conductor Effect

There are two types of transmission line conductors: overhead and underground. Overhead conductors, made of naked metal and suspended on insulators, are preferred over underground conductors because of the lower cost and easy maintenance. Also, overhead transmission lines use aluminum conductors, because of the lower cost and lighter weight compared to copper conductors, although more cross-section area is needed to conduct the same amount of current. There are different types of commercially available aluminum conductors: aluminum-conductor-steel-reinforced (ACSR), aluminum-conductor-alloy-reinforced (ACAR), all-aluminum-conductor (AAC), and all-aluminum-alloy-conductor (AAAC).

TABLE 13.1 Resistivity and Temperature Coefficient of Some Conductors

Material	Resistivity at 20°C ($\Omega\text{-m}$)	Temperature Coefficient ($^{\circ}\text{C}$)
Silver	1.59×10^{-8}	243.0
Annealed copper	1.72×10^{-8}	234.5
Hard-drawn copper	1.77×10^{-8}	241.5
Aluminum	2.83×10^{-8}	228.1

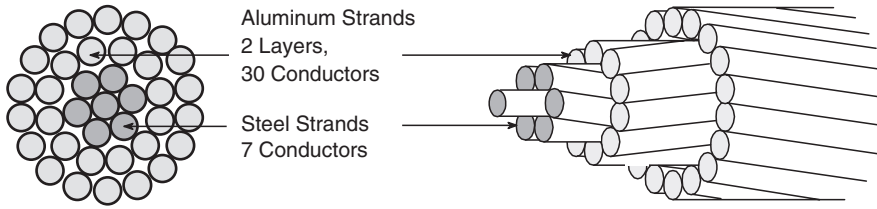


FIGURE 13.4 Stranded aluminum conductor with stranded steel core (ACSR).

ACSR is one of the most used conductors in transmission lines. It consists of alternate layers of stranded conductors, spiraled in opposite directions to hold the strands together, surrounding a core of steel strands. Figure 13.4 shows an example of aluminum and steel strands combination.

The purpose of introducing a steel core inside the stranded aluminum conductors is to obtain a high strength-to-weight ratio. A stranded conductor offers more flexibility and easier to manufacture than a solid large conductor. However, the total resistance is increased because the outside strands are larger than the inside strands on account of the spiraling [8]. The resistance of each wound conductor at any layer, per unit length, is based on its total length as follows:

$$R_{\text{cond}} = \frac{\rho}{A} \sqrt{1 + \left(\pi \frac{1}{p}\right)^2} (\Omega/\text{m}) \quad (13.4)$$

where R_{cond} = resistance of wound conductor (Ω)

$$\sqrt{1 + \left(\pi \frac{1}{p}\right)^2} = \text{length of wound conductor (m)}$$

$$p_{\text{cond}} = \frac{l_{\text{turn}}}{2r_{\text{layer}}} = \text{relative pitch of wound conductor}$$

$$l_{\text{turn}} = \text{length of one turn of the spiral (m)}$$

$$2r_{\text{layer}} = \text{diameter of the layer (m)}$$

The parallel combination of n conductors, with same diameter per layer, gives the resistance per layer as follows:

$$R_{\text{layer}} = \frac{1}{\sum_{i=1}^n \frac{1}{R_i}} (\Omega/\text{m}) \quad (13.5)$$

Similarly, the total resistance of the stranded conductor is evaluated by the parallel combination of resistances per layer.

In high-voltage transmission lines, there may be more than one conductor per phase (bundle configuration) to increase the current capability and to reduce corona effect discharge. Corona effect occurs when the surface potential gradient of a conductor exceeds the dielectric strength of the surrounding air (30 kV/cm during fair weather), producing ionization in the area close to the conductor, with consequent corona losses, audible noise, and radio interference. As corona effect is a function of conductor diameter, line configuration, and conductor surface condition, then meteorological conditions play a key role in its evaluation. Corona losses under rain or snow, for instance, are much higher than in dry weather.

Corona, however, can be reduced by increasing the total conductor surface. Although corona losses rely on meteorological conditions, their evaluation takes into account the conductance between conductors and between conductors and ground. By increasing the number of conductors per phase, the total cross-section area increases, the current capacity increases, and the total AC resistance decreases proportionally to the number of conductors per bundle. Conductor bundles may be applied to any

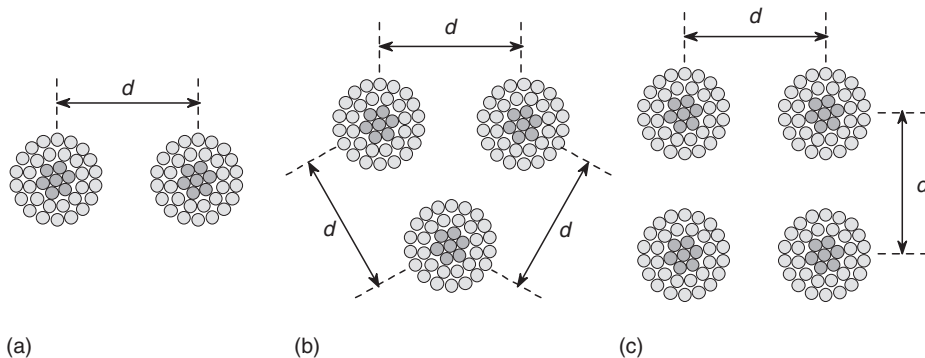


FIGURE 13.5 Stranded conductors arranged in bundles per phase of (a) two, (b) three, and (c) four.

voltage but are always used at 345 kV and above to limit corona. To maintain the distance between bundle conductors along the line, spacers made of steel or aluminum bars are used. Figure 13.5 shows some typical arrangement of stranded bundle configurations.

13.3 Current-Carrying Capacity (Ampacity)

In overhead transmission lines, the current-carrying capacity is determined mostly by the conductor resistance and the heat dissipated from its surface [8]. The heat generated in a conductor (Joule's effect) is dissipated from its surface area by convection and radiation given by

$$I^2R = S(w_c + w_r) \text{ (W)} \quad (13.6)$$

where R = conductor resistance (Ω)

I = conductor current-carrying (A)

S = conductor surface area (sq. in.)

w_c = convection heat loss (W/sq. in.)

w_r = radiation heat loss (W/sq. in.)

Heat dissipation by convection is defined as

$$w_c = \frac{0.0128\sqrt{pv}}{T_{\text{air}}^{0.123}\sqrt{d_{\text{cond}}}} \Delta t \text{ (W)} \quad (13.7)$$

where p = atmospheric pressure (atm)

v = wind velocity (ft/s)

d_{cond} = conductor diameter (in.)

T_{air} = air temperature (kelvin)

$\Delta t = T_c - T_{\text{air}}$ = temperature rise of the conductor ($^{\circ}\text{C}$)

Heat dissipation by radiation is obtained from Stefan–Boltzmann law and is defined as

$$w_r = 36.8 E \left[\left(\frac{T_c}{1000} \right)^4 - \left(\frac{T_{\text{air}}}{1000} \right)^4 \right] \text{ (W/sq. in.)} \quad (13.8)$$

where w_r = radiation heat loss (W/sq. in.)

E = emissivity constant (1 for the absolute black body and 0.5 for oxidized copper)

T_c = conductor temperature ($^{\circ}\text{C}$)

T_{air} = ambient temperature ($^{\circ}\text{C}$)

Substituting Eqs. (13.7) and (13.8) in Eq. (13.6) we can obtain the conductor ampacity at given temperatures

$$I = \sqrt{\frac{S(w_c + w_r)}{R}} \quad (\text{A}) \quad (13.9)$$

$$I = \sqrt{\frac{S}{R} \left(\frac{\Delta t (0.0128 \sqrt{pv})}{T_{\text{air}}^{0.123} \sqrt{d_{\text{cond}}}} + 36.8 E \left(\frac{T_c^4 - T_{\text{air}}^4}{1000^4} \right) \right)} \quad (\text{A}) \quad (13.10)$$

Some approximated current-carrying capacity for overhead ACSR and AACs are presented in the section “Characteristics of Overhead Conductors” [3,9].

13.4 Inductance and Inductive Reactance

A current-carrying conductor produces concentric magnetic flux lines around the conductor. If the current varies with the time, the magnetic flux changes and a voltage is induced. Therefore, an inductance is present, defined as the ratio of the magnetic flux linkage and the current. The magnetic flux produced by the current in transmission line conductors produces a total inductance whose magnitude depends on the line configuration. To determine the inductance of the line, it is necessary to calculate, as in any magnetic circuit with permeability μ , the following factors:

1. Magnetic field intensity H
2. Magnetic field density B
3. Flux linkage λ

13.4.1 Inductance of a Solid, Round, Infinitely Long Conductor

Consider an infinitely long, solid cylindrical conductor with radius r , carrying current I as shown in Fig. 13.6. If the conductor is made of a nonmagnetic material, and the current is assumed uniformly distributed (no skin effect), then the generated internal and external magnetic field lines are concentric circles around the conductor with direction defined by the right-hand rule.

13.4.2 Internal Inductance Due to Internal Magnetic Flux

To obtain the internal inductance, a magnetic field with radius x inside the conductor of length l is chosen, as shown in Fig. 13.7.

The fraction of the current I_x enclosed in the area of the circle chosen is determined by

$$I_x = I \frac{\pi x^2}{\pi r^2} \quad (\text{A}) \quad (13.11)$$

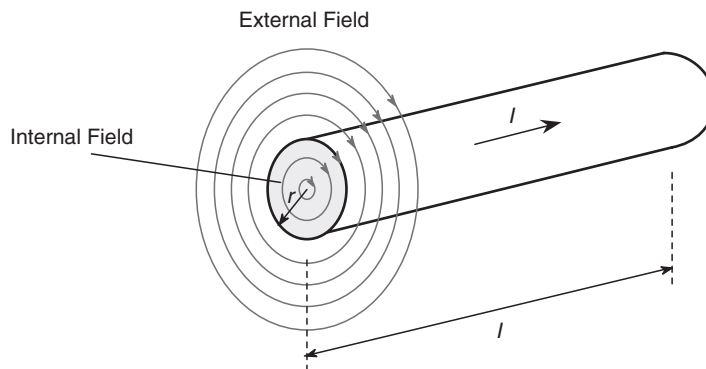


FIGURE 13.6 External and internal concentric magnetic flux lines around the conductor.

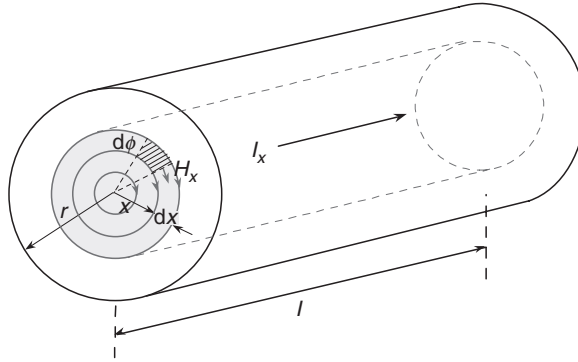


FIGURE 13.7 Internal magnetic flux.

Ampere's law determines the magnetic field intensity H_x , constant at any point along the circle contour as

$$H_x = \frac{I_x}{2\pi x} = \frac{I}{2\pi r^2} x \text{ (A/m)} \quad (13.12)$$

The magnetic flux density B_x is obtained by

$$B_x = \mu H_x = \frac{\mu_0}{2\pi} \left(\frac{Ix}{r^2} \right) \text{ (T)} \quad (13.13)$$

where $\mu = \mu_0 = 4\pi \times 10^{-7} \text{ H/m}$ for a nonmagnetic material.

The differential flux $d\phi$ enclosed in a ring of thickness dx for a 1-m length of conductor and the differential flux linkage $d\lambda$ in the respective area are

$$d\phi = B_x dx = \frac{\mu_0}{2\pi} \left(\frac{Ix}{r^2} \right) dx \text{ (Wb/m)} \quad (13.14)$$

$$d\lambda = \frac{\pi x^2}{\pi r^2} d\phi = \frac{\mu_0}{2\pi} \left(\frac{Ix^3}{r^4} \right) dx \text{ (Wb/m)} \quad (13.15)$$

The internal flux linkage is obtained by integrating the differential flux linkage from $x = 0$ to $x = r$

$$\lambda_{\text{int}} = \int_0^r d\lambda = \frac{\mu_0}{8\pi} I \text{ (Wb/m)} \quad (13.16)$$

Therefore, the conductor inductance due to internal flux linkage, per unit length, becomes

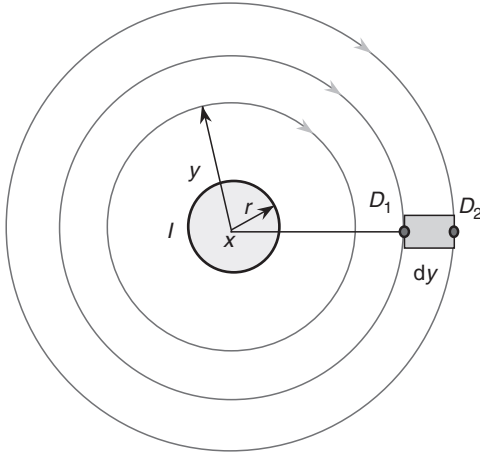
$$L_{\text{int}} = \frac{\lambda_{\text{int}}}{I} = \frac{\mu_0}{8\pi} \text{ (H/m)} \quad (13.17)$$

13.4.3 External Inductance

The external inductance is evaluated assuming that the total current I is concentrated at the conductor surface (maximum skin effect). At any point on an external magnetic field circle of radius y (Fig. 13.8), the magnetic field intensity H_y and the magnetic field density B_y , per unit length, are

$$H_y = \frac{I}{2\pi y} \text{ (A/m)} \quad (13.18)$$

$$B_y = \mu H_y = \frac{\mu_0}{2\pi} \frac{I}{y} \text{ (T)} \quad (13.19)$$



The differential flux $d\phi$ enclosed in a ring of thickness dy , from point D_1 to point D_2 , for a 1-m length of conductor is

$$d\phi = B_y dy = \frac{\mu_0}{2\pi} \frac{I}{y} dy \text{ (Wb/m)} \quad (13.20)$$

As the total current I flows in the surface conductor, then the differential flux linkage $d\lambda$ has the same magnitude as the differential flux $d\phi$.

$$d\lambda = d\phi = \frac{\mu_0}{2\pi} \frac{I}{y} dy \text{ (Wb/m)} \quad (13.21)$$

The total external flux linkage enclosed by the ring is obtained by integrating from D_1 to D_2

FIGURE 13.8 External magnetic field.

$$\lambda_{1-2} = \int_{D_1}^{D_2} d\lambda = \frac{\mu_0}{2\pi} I \int_{D_1}^{D_2} \frac{dy}{y} = \frac{\mu_0}{2\pi} I \ln\left(\frac{D_1}{D_2}\right) \text{ (Wb/m)} \quad (13.22)$$

In general, the total external flux linkage from the surface of the conductor to any point D , per unit length, is

$$\lambda_{\text{ext}} = \int_r^D d\lambda = \frac{\mu_0}{2\pi} I \ln\left(\frac{D}{r}\right) \text{ (Wb/m)} \quad (13.23)$$

The summation of the internal and external flux linkage at any point D permits evaluation of the total inductance of the conductor L_{tot} , per unit length, as follows:

$$\lambda_{\text{intl}} + \lambda_{\text{ext}} = \frac{\mu_0}{2\pi} I \left[\frac{1}{4} + \ln\left(\frac{D}{r}\right) \right] = \frac{\mu_0}{2\pi} I \ln\left(\frac{D}{e^{-1/4}r}\right) \text{ (Wb/m)} \quad (13.24)$$

$$L_{\text{tot}} = \frac{\lambda_{\text{int}} + \lambda_{\text{ext}}}{I} = \frac{\mu_0}{2\pi} \ln\left(\frac{D}{\text{GMR}}\right) \text{ (H/m)} \quad (13.25)$$

where GMR (geometric mean radius) $= e^{-1/4}r = 0.7788r$

GMR can be considered as the radius of a fictitious conductor assumed to have no internal flux but with the same inductance as the actual conductor with radius r .

13.4.4 Inductance of a Two-Wire Single-Phase Line

Now, consider a two-wire single-phase line with solid cylindrical conductors A and B with the same radius r , same length l , and separated by a distance D , where $D > r$, and conducting the same current I , as shown in Fig. 13.9. The current flows from the source to the load in conductor A and returns in conductor B ($I_A = -I_B$).

The magnetic flux generated by one conductor links the other conductor. The total flux linking conductor A, for instance, has two components: (a) the flux generated by conductor A and (b) the flux generated by conductor B which links conductor A.

As shown in Fig. 13.10, the total flux linkage from conductors A and B at point P is

$$\lambda_{AP} = \lambda_{AAP} + \lambda_{ABP} \quad (13.26)$$

$$\lambda_{BP} = \lambda_{BBP} + \lambda_{BAP} \quad (13.27)$$

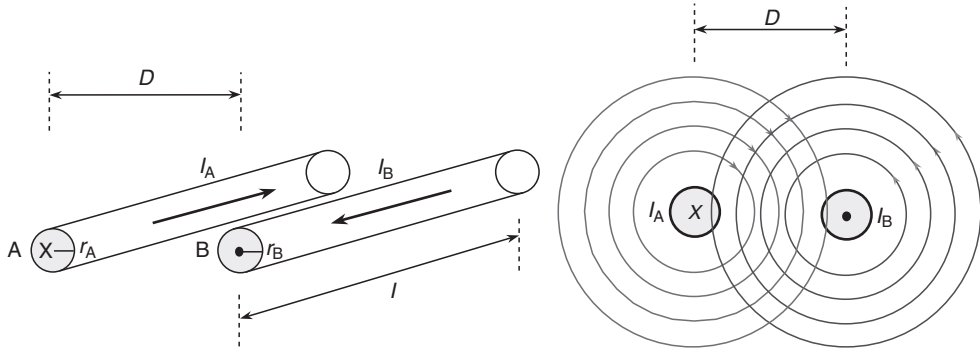


FIGURE 13.9 External magnetic flux around conductors in a two-wire single-phase line.

where λ_{AAP} = flux linkage from magnetic field of conductor A on conductor A at point P

λ_{ABP} = flux linkage from magnetic field of conductor B on conductor A at point P

λ_{BBP} = flux linkage from magnetic field of conductor B on conductor B at point P

λ_{BAP} = flux linkage from magnetic field of conductor A on conductor B at point P

The expressions of the flux linkages above, per unit length, are

$$\lambda_{AAP} = \frac{\mu_0}{2\pi} I \ln \left(\frac{D_{AP}}{\text{GMR}_A} \right) \text{ (Wb/m)} \quad (13.28)$$

$$\lambda_{ABP} = \int_D^{D_{BP}} B_{BP} \, dP = -\frac{\mu_0}{2\pi} I \ln \left(\frac{D_{BP}}{D} \right) \text{ (Wb/m)} \quad (13.29)$$

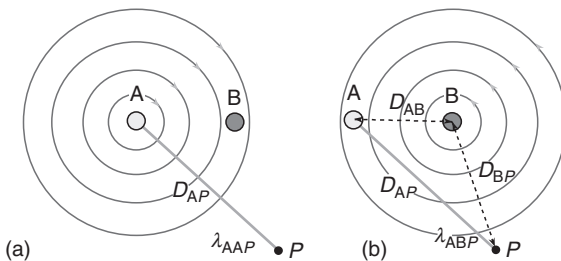
$$\lambda_{BAP} = \int_D^{D_{AP}} B_{AP} \, dP = -\frac{\mu_0}{2\pi} I \ln \left(\frac{D_{AP}}{D} \right) \text{ (Wb/m)} \quad (13.30)$$

$$\lambda_{BBP} = \frac{\mu_0}{2\pi} I \ln \left(\frac{D_{BP}}{\text{GMR}_B} \right) \text{ (Wb/m)} \quad (13.31)$$

The total flux linkage of the system at point P is the algebraic summation of λ_{AP} and λ_{BP}

$$\lambda_P = \lambda_{AP} + \lambda_{BP} = (\lambda_{AAP} + \lambda_{ABP}) + (\lambda_{BAP} + \lambda_{BBP}) \quad (13.32)$$

$$\lambda_P = \frac{\mu_0}{2\pi} I \ln \left[\left(\frac{D_{AP}}{\text{GMR}_A} \right) \left(\frac{D}{D_{AP}} \right) \left(\frac{D_{BP}}{\text{GMR}_B} \right) \left(\frac{D}{D_{BP}} \right) \right] = \frac{\mu_0}{2\pi} I \ln \left(\frac{D^2}{\text{GMR}_A \text{GMR}_B} \right) \text{ (Wb/m)} \quad (13.33)$$



If the conductors have the same radius, $r_A = r_B = r$, and the point P is shifted to infinity, then the total flux linkage of the system becomes

$$\lambda = \frac{\mu_0}{\pi} I \ln \left(\frac{D}{\text{GMR}} \right) \text{ (Wb/m)} \quad (13.34)$$

FIGURE 13.10 Flux linkage of (a) conductor A at point P and (b) conductor B on conductor A at point P. Single-phase system.

and the total inductance per unit length becomes

$$L_{1\text{-phase system}} = \frac{\lambda}{I} = \frac{\mu_0}{\pi} \ln\left(\frac{D}{\text{GMR}}\right) \text{ (H/m)} \quad (13.35)$$

Comparing Eqs. (13.25) and (13.35), it can be seen that the inductance of the single-phase system is twice the inductance of a single conductor.

For a line with stranded conductors, the inductance is determined using a new GMR value named $\text{GMR}_{\text{stranded}}$, evaluated according to the number of conductors. If conductors A and B in the single-phase system, are formed by n and m solid cylindrical identical subconductors in parallel, respectively, then

$$\text{GMR}_{\text{A-stranded}} = \sqrt[n^2]{\prod_{i=1}^n \prod_{j=1}^n D_{ij}} \quad (13.36)$$

$$\text{GMR}_{\text{B-stranded}} = \sqrt[m^2]{\prod_{i=1}^m \prod_{j=1}^m D_{ij}} \quad (13.37)$$

Generally, the $\text{GMR}_{\text{stranded}}$ for a particular cable can be found in conductor tables given by the manufacturer.

If the line conductor is composed of bundle conductors, the inductance is reevaluated taking into account the number of bundle conductors and the separation among them. The $\text{GMR}_{\text{bundle}}$ is introduced to determine the final inductance value. Assuming the same separation among bundle conductors, the equation for $\text{GMR}_{\text{bundle}}$, up to three conductors per bundle, is defined as

$$\text{GMR}_{n \text{ bundle conductors}} = \sqrt[n]{d^{n-1} \text{GMR}_{\text{stranded}}} \quad (13.38)$$

where n = number of conductors per bundle

$\text{GMR}_{\text{stranded}}$ = GMR of the stranded conductor

d = distance between bundle conductors

For four conductors per bundle with the same separation between consecutive conductors, the $\text{GMR}_{\text{bundle}}$ is evaluated as

$$\text{GMR}_{4 \text{ bundle conductors}} = 1.09 \sqrt[4]{d^3 \text{GMR}_{\text{stranded}}} \quad (13.39)$$

13.4.5 Inductance of a Three-Phase Line

The derivations for the inductance in a single-phase system can be extended to obtain the inductance per phase in a three-phase system. Consider a three-phase, three-conductor system with solid cylindrical conductors with identical radius r_A , r_B , and r_C , placed horizontally with separation D_{AB} , D_{BC} , and D_{CA} (where $D > r$) among them. Corresponding currents I_A , I_B , and I_C flow along each conductor as shown in Fig. 13.11.

The total magnetic flux enclosing conductor A at a point P away from the conductors is the sum of the flux produced by conductors A, B, and C as follows:

$$\phi_{AP} = \phi_{AAP} + \phi_{ABP} + \phi_{ACP} \quad (13.40)$$

where ϕ_{AAP} = flux produced by current I_A on conductor A at point P

ϕ_{ABP} = flux produced by current I_B on conductor A at point P

ϕ_{ACP} = flux produced by current I_C on conductor A at point P

Considering 1-m length for each conductor, the expressions for the fluxes above are

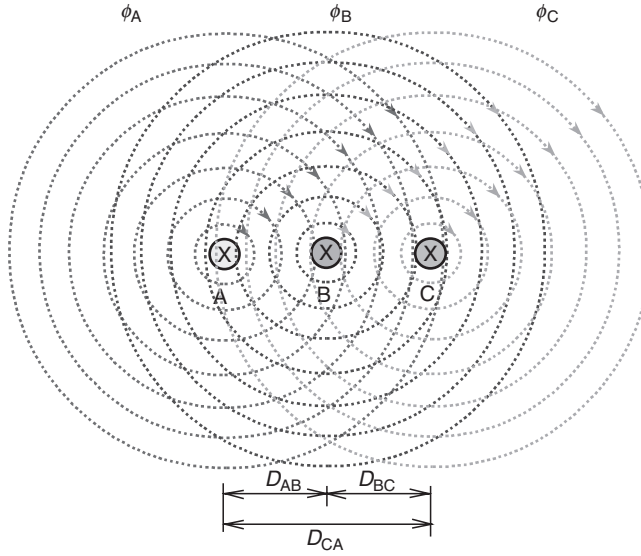


FIGURE 13.11 Magnetic flux produced by each conductor in a three-phase system.

$$\phi_{AAP} = \frac{\mu_0}{2\pi} I_A \ln \left(\frac{D_{AP}}{\text{GMR}_A} \right) \text{ (Wb/m)} \quad (13.41)$$

$$\phi_{ABP} = \frac{\mu_0}{2\pi} I_B \ln \left(\frac{D_{BP}}{D_{AB}} \right) \text{ (Wb/m)} \quad (13.42)$$

$$\phi_{ACP} = \frac{\mu_0}{2\pi} I_C \ln \left(\frac{D_{CP}}{D_{AC}} \right) \text{ (Wb/m)} \quad (13.43)$$

The corresponding flux linkage of conductor A at point P (Fig. 13.12) is evaluated as

$$\lambda_{AP} = \lambda_{AAP} + \lambda_{ABP} + \lambda_{ACP} \quad (13.44)$$

having

$$\lambda_{AAP} = \frac{\mu_0}{2\pi} I_A \ln \left(\frac{D_{AP}}{\text{GMR}_A} \right) \text{ (Wb/m)} \quad (13.45)$$

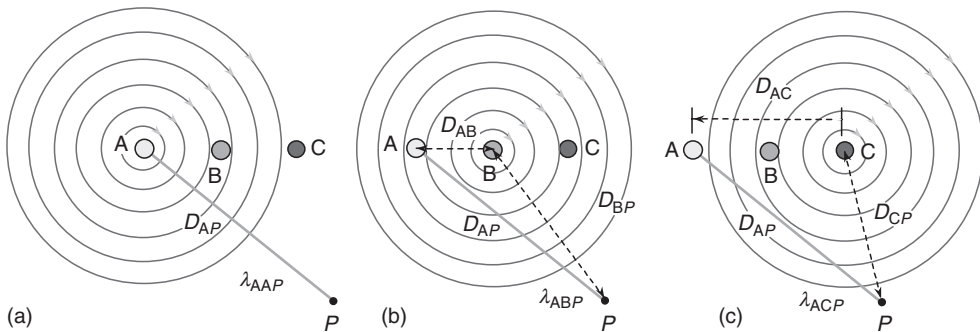


FIGURE 13.12 Flux linkage of (a) conductor A at point P , (b) conductor B on conductor A at point P , and (c) conductor C on conductor A at point P . Three-phase system.

$$\lambda_{ABP} = \int_{D_{AB}}^{D_{BP}} B_{BP} dP = \frac{\mu_0}{2\pi} I_B \ln \left(\frac{D_{BP}}{D_{AB}} \right) \text{ (Wb/m)} \quad (13.46)$$

$$\lambda_{ACP} = \int_{D_{AC}}^{D_{CP}} B_{CP} dP = \frac{\mu_0}{2\pi} I_C \ln \left(\frac{D_{CP}}{D_{AC}} \right) \text{ (Wb/m)} \quad (13.47)$$

where λ_{AP} = total flux linkage of conductor A at point P

λ_{AAP} = flux linkage from magnetic field of conductor A on conductor A at point P

λ_{ABP} = flux linkage from magnetic field of conductor B on conductor A at point P

λ_{ACP} = flux linkage from magnetic field of conductor C on conductor A at point P

Substituting Eqs. (13.45) through (13.47) in Eq. (13.44) and rearranging, according to natural logarithms law, we have

$$\lambda_{AP} = \frac{\mu_0}{2\pi} \left[I_A \ln \left(\frac{D_{AP}}{\text{GMR}_A} \right) + I_B \ln \left(\frac{D_{BP}}{D_{AB}} \right) + I_C \ln \left(\frac{D_{CP}}{D_{AC}} \right) \right] \text{ (Wb/m)} \quad (13.48)$$

$$\begin{aligned} \lambda_{AP} = & \frac{\mu_0}{2\pi} \left[I_A \ln \left(\frac{1}{\text{GMR}_A} \right) + I_B \ln \left(\frac{1}{D_{AB}} \right) + I_C \ln \left(\frac{1}{D_{AC}} \right) \right] \\ & + \frac{\mu_0}{2\pi} [I_A \ln(D_{AP}) + I_B \ln(D_{BP}) + I_C \ln(D_{CP})] \text{ (Wb/m)} \end{aligned} \quad (13.49)$$

The arrangement of Eq. (13.48) into Eq. (13.49) is algebraically correct according to natural logarithms law. However, as the calculation of any natural logarithm must be dimensionless, the numerator in the expressions $\ln(1/\text{GMR}_A)$, $\ln(1/D_{AB})$, and $\ln(1/D_{AC})$ must have the same dimension as the denominator. The same applies for the denominator in the expressions $\ln(D_{AP})$, $\ln(D_{BP})$, and $\ln(D_{CP})$.

Assuming a balanced three-phase system, where $I_A + I_B + I_C = 0$, and shifting the point P to infinity in such a way that $D_{AP} = D_{BP} = D_{CP}$, then the second part of Eq. (13.49) is zero, and the flux linkage of conductor A becomes

$$\lambda_A = \frac{\mu_0}{2\pi} \left[I_A \ln \left(\frac{1}{\text{GMR}_A} \right) + I_B \ln \left(\frac{1}{D_{AB}} \right) + I_C \ln \left(\frac{1}{D_{AC}} \right) \right] \text{ (Wb/m)} \quad (13.50)$$

Similarly, the flux linkage expressions for conductors B and C are

$$\lambda_B = \frac{\mu_0}{2\pi} \left[I_A \ln \left(\frac{1}{D_{BA}} \right) + I_B \ln \left(\frac{1}{\text{GMR}_B} \right) + I_C \ln \left(\frac{1}{D_{BC}} \right) \right] \text{ (Wb/m)} \quad (13.51)$$

$$\lambda_C = \frac{\mu_0}{2\pi} \left[I_A \ln \left(\frac{1}{D_{CA}} \right) + I_B \ln \left(\frac{1}{D_{CB}} \right) + I_C \ln \left(\frac{1}{\text{GMR}_C} \right) \right] \text{ (Wb/m)} \quad (13.52)$$

The flux linkage of each phase conductor depends on the three currents, and therefore, the inductance per phase is not only one as in the single-phase system. Instead, three different inductances (self and mutual conductor inductances) exist. Calculating the inductance values from the equations above and arranging the equations in a matrix form we can obtain the set of inductances in the system

$$\begin{bmatrix} \lambda_A \\ \lambda_B \\ \lambda_C \end{bmatrix} = \begin{bmatrix} L_{AA} & L_{AB} & L_{AC} \\ L_{BA} & L_{BB} & L_{BC} \\ L_{CA} & L_{CB} & L_{CC} \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad (13.53)$$

where λ_A , λ_B , λ_C = total flux linkages of conductors A, B, and C

L_{AA} , L_{BB} , L_{CC} = self-inductances of conductors A, B, and C field of conductor A at point P

L_{AB} , L_{BC} , L_{CA} , L_{BA} , L_{CB} , L_{AC} = mutual inductances among conductors

With nine different inductances in a simple three-phase system the analysis could be a little more complicated. However, a single inductance per phase can be obtained if the three conductors are arranged with the same separation among them (symmetrical arrangement), where $D = D_{AB} = D_{BC} = D_{CA}$. For a balanced three-phase system ($I_A + I_B + I_C = 0$, or $I_A = -I_B - I_C$), the flux linkage of each conductor, per unit length, will be the same. From Eq. (13.50) we have

$$\begin{aligned}\lambda_A &= \frac{\mu_0}{2\pi} \left[(-I_B - I_C) \ln \left(\frac{1}{\text{GMR}_A} \right) + I_B \ln \left(\frac{1}{D} \right) + I_C \ln \left(\frac{1}{D} \right) \right] \\ \lambda_A &= \frac{\mu_0}{2\pi} \left[-I_B \ln \left(\frac{D}{\text{GMR}_A} \right) - I_C \ln \left(\frac{D}{\text{GMR}_A} \right) \right] \\ \lambda_A &= \frac{\mu_0}{2\pi} \left[I_A \ln \left(\frac{D}{\text{GMR}_A} \right) \right] \text{ (Wb/m)}\end{aligned}\quad (13.54)$$

If GMR value is the same for all conductors (either single or bundle GMR), the total flux linkage expression is the same for all phases. Therefore, the equivalent inductance per phase is

$$L_{\text{phase}} = \frac{\mu_0}{2\pi} \ln \left(\frac{D}{\text{GMR}_{\text{phase}}} \right) \text{ (H/m)} \quad (13.55)$$

13.4.6 Inductance of Transposed Three-Phase Transmission Lines

In actual transmission lines, the phase conductors cannot maintain symmetrical arrangement along the whole length because of construction considerations, even when bundle conductor spacers are used. With asymmetrical spacing, the inductance will be different for each phase, with a corresponding unbalanced voltage drop on each conductor. Therefore, the single-phase equivalent circuit to represent the power system cannot be used.

However, it is possible to assume symmetrical arrangement in the transmission line by transposing the phase conductors. In a transposed system, each phase conductor occupies the location of the other two phases for one-third of the total line length as shown in Fig. 13.13. In this case, the average distance geometrical mean distance (GMD) substitutes distance D , and the calculation of phase inductance derived for symmetrical arrangement is still valid.

The inductance per phase per unit length in a transmission line becomes

$$L_{\text{phase}} = \frac{\mu_0}{2\pi} \ln \left(\frac{\text{GMD}}{\text{GMR}_{\text{phase}}} \right) \text{ (H/m)} \quad (13.56)$$

Once the inductance per phase is obtained, the inductive reactance per unit length is

$$X_{L_{\text{phase}}} = 2\pi f L_{\text{phase}} = \mu_0 f \ln \left(\frac{\text{GMD}}{\text{GMR}_{\text{phase}}} \right) \text{ (}\Omega/\text{m)} \quad (13.57)$$

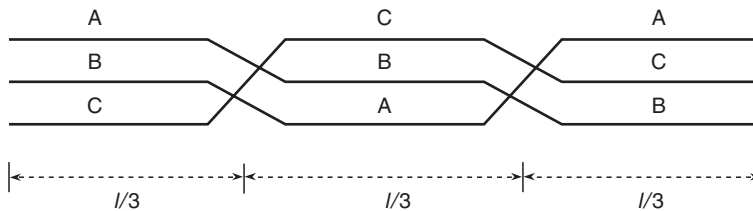


FIGURE 13.13 Arrangement of conductors in a transposed line.

For bundle conductors, the $\text{GMR}_{\text{bundle}}$ value is determined, as in the single-phase transmission line case, by the number of conductors, and by the number of conductors per bundle and the separation among them. The expression for the total inductive reactance per phase yields

$$X_{L_{\text{phase}}} = \mu_0 f \ln \left(\frac{\text{GMD}}{\text{GMR}_{\text{bundle}}} \right) (\Omega/\text{m}) \quad (13.58)$$

where $\text{GMR}_{\text{bundle}} = (d^{n-1} \text{GMR}_{\text{stranded}})^{1/n}$ up to three conductors per bundle (m)
 $\text{GMR}_{\text{bundle}} = 1.09(d^4 \text{GMR}_{\text{stranded}})^{1/4}$ for four conductors per bundle (m)
 $\text{GMR}_{\text{phase}}$ = geometric mean radius of phase conductor, either solid or stranded (m)
 $\text{GMD} = \sqrt[3]{D_{AB}D_{BC}D_{CA}}$ = geometrical mean distance for a three-phase line (m)
 d = distance between bundle conductors (m)
 n = number of conductor per bundle
 f = frequency (Hz)

13.5 Capacitance and Capacitive Reactance

Capacitance exists among transmission line conductors due to their potential difference. To evaluate the capacitance between conductors in a surrounding medium with permittivity ϵ , it is necessary to determine the voltage between the conductors, and the electric field strength of the surrounding.

13.5.1 Capacitance of a Single-Solid Conductor

Consider a solid, cylindrical, long conductor with radius r , in a free space with permittivity ϵ_0 , and with a charge of q^+ coulombs per meter, uniformly distributed on the surface. There is a constant electric field strength on the surface of cylinder (Fig. 13.14). The resistivity of the conductor is assumed to be zero (perfect conductor), which results in zero internal electric field due to the charge on the conductor.

The charge q^+ produces an electric field radial to the conductor with equipotential surfaces concentric to the conductor. According to Gauss's law, the total electric flux leaving a closed surface is equal to the total charge inside the volume enclosed by the surface. Therefore, at an outside point P separated x meters from the center of the conductor, the electric field flux density and the electric field intensity are

$$\text{Density}_P = \frac{q}{A} = \frac{q}{2\pi x} \text{ (C)} \quad (13.59)$$

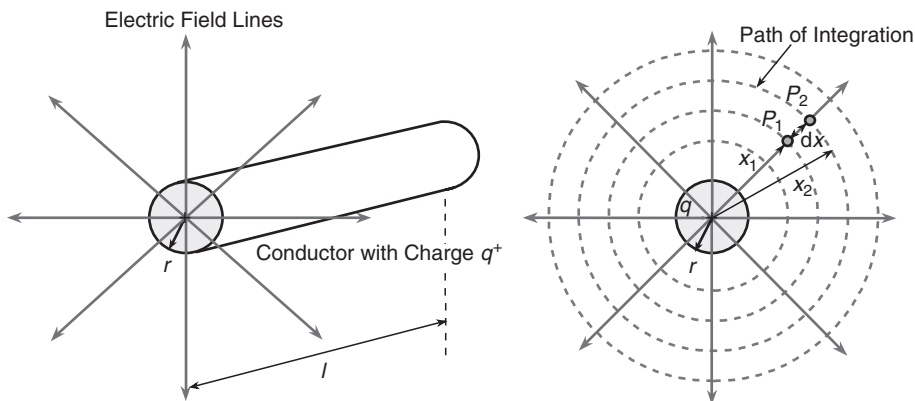


FIGURE 13.14 Electric field produced from a single conductor.

$$E_P = \frac{\text{Density}_P}{\varepsilon} = \frac{q}{2\pi\varepsilon_0 x} \quad (\text{V/m}) \quad (13.60)$$

where Density_P = electric flux density at point P

E_P = electric field intensity at point P

A = surface of a concentric cylinder with 1-m length and radius x (m^2)

$\varepsilon = \varepsilon_0 = \frac{10^{-9}}{36\pi}$ = permittivity of free space assumed for the conductor (F/m)

The potential difference or voltage difference between two outside points P_1 and P_2 with corresponding distances x_1 and x_2 from the conductor center is defined by integrating the electric field intensity from x_1 to x_2

$$V_{1-2} = \int_{x_1}^{x_2} E_P \frac{dx}{x} = \int_{x_1}^{x_2} \frac{q}{2\pi\varepsilon_0} \frac{dx}{x} = \frac{q}{2\pi\varepsilon_0} \ln \left[\frac{x_2}{x_1} \right] \quad (\text{V}) \quad (13.61)$$

Then, the capacitance between points P_1 and P_2 is evaluated as

$$C_{1-2} = \frac{q}{V_{1-2}} = \frac{2\pi\varepsilon_0}{\ln \left[\frac{x_2}{x_1} \right]} \quad (\text{F/m}) \quad (13.62)$$

If point P_1 is located at the conductor surface ($x_1 = r$), and point P_2 is located at ground surface below the conductor ($x_2 = h$), then the voltage of the conductor and the capacitance between the conductor and ground are

$$V_{\text{cond}} = \frac{q}{2\pi\varepsilon_0} \ln \left[\frac{h}{r} \right] \quad (\text{V}) \quad (13.63)$$

$$C_{\text{cond-ground}} = \frac{q}{V_{\text{cond}}} = \frac{2\pi\varepsilon_0}{\ln \left[\frac{h}{r} \right]} \quad (\text{F/m}) \quad (13.64)$$

13.5.2 Capacitance of a Single-Phase Line with Two Wires

Consider a two-wire single-phase line with conductors A and B with the same radius r , separated by a distance $D > r_A$ and r_B . The conductors are energized by a voltage source such that conductor A has a charge q^+ and conductor B a charge q^- as shown in Fig. 13.15.

The charge on each conductor generates independent electric fields. Charge q^+ on conductor A generates a voltage V_{AB-A} between both conductors. Similarly, charge q^- on conductor B generates a voltage V_{AB-B} between conductors.

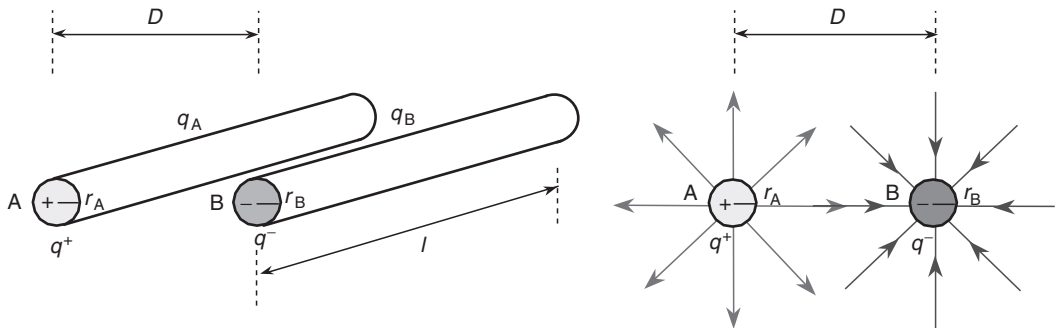


FIGURE 13.15 Electric field produced from a two-wire single-phase system.

V_{AB-A} is calculated by integrating the electric field intensity, due to the charge on conductor A, on conductor B from r_A to D

$$V_{AB-A} = \int_{r_A}^D E_A dx = \frac{q}{2\pi\epsilon_0} \ln \left[\frac{D}{r_A} \right] \quad (13.65)$$

V_{AB-B} is calculated by integrating the electric field intensity due to the charge on conductor B from D to r_B

$$V_{AB-B} = \int_D^{r_B} E_B dx = \frac{-q}{2\pi\epsilon_0} \ln \left[\frac{r_B}{D} \right] \quad (13.66)$$

The total voltage is the sum of the generated voltages V_{AB-A} and V_{AB-B}

$$V_{AB} = V_{AB-A} + V_{AB-B} = \frac{q}{2\pi\epsilon_0} \ln \left[\frac{D}{r_A} \right] - \frac{q}{2\pi\epsilon_0} \ln \left[\frac{r_B}{D} \right] = \frac{q}{2\pi\epsilon_0} \ln \left[\frac{D^2}{r_A r_B} \right] \quad (13.67)$$

If the conductors have the same radius, $r_A = r_B = r$, then the voltage between conductors V_{AB} , and the capacitance between conductors C_{AB} , for a 1-m line length are

$$V_{AB} = \frac{q}{\pi\epsilon_0} \ln \left[\frac{D}{r} \right] \text{ (V)} \quad (13.68)$$

$$C_{AB} = \frac{\pi\epsilon_0}{\ln \left[\frac{D}{r} \right]} \text{ (F/m)} \quad (13.69)$$

The voltage between each conductor and ground (G) (Fig. 13.16) is one-half of the voltage between the two conductors. Therefore, the capacitance from either line to ground is twice the capacitance between lines

$$V_{AG} = V_{BG} = \frac{V_{AB}}{2} \text{ (V)} \quad (13.70)$$

$$C_{AG} = \frac{q}{V_{AG}} = \frac{2\pi\epsilon_0}{\ln \left[\frac{D}{r} \right]} \text{ (F/m)} \quad (13.71)$$

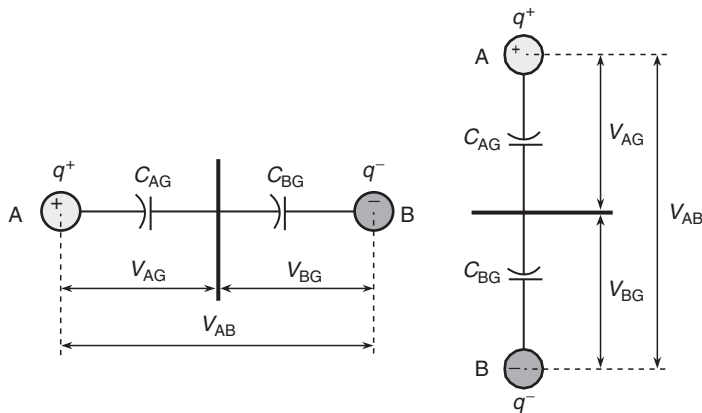


FIGURE 13.16 Capacitance between line to ground in a two-wire single-phase line.

13.5.3 Capacitance of a Three-Phase Line

Consider a three-phase line with the same voltage magnitude between phases, and assuming a balanced system with abc (positive) sequence such that $q_A + q_B + q_C = 0$. The conductors have radii r_A , r_B , and r_C , and the space between conductors are D_{AB} , D_{BC} , and D_{AC} (where D_{AB} , D_{BC} , and $D_{AC} > r_A$, r_B , and r_C). Also, the effect of earth and neutral conductors is neglected.

The expression for voltages between two conductors in a single-phase system can be extended to obtain the voltages between conductors in a three-phase system. The expressions for V_{AB} and V_{AC} are

$$V_{AB} = \frac{1}{2\pi\epsilon_0} \left[q_A \ln \left[\frac{D_{AB}}{r_A} \right] + q_B \ln \left[\frac{r_B}{D_{AB}} \right] + q_C \ln \left[\frac{D_{BC}}{D_{AC}} \right] \right] \quad (\text{V}) \quad (13.72)$$

$$V_{AC} = \frac{1}{2\pi\epsilon_0} \left[q_A \ln \left[\frac{D_{CA}}{r_A} \right] + q_B \ln \left[\frac{D_{BC}}{D_{AB}} \right] + q_C \ln \left[\frac{r_C}{D_{AC}} \right] \right] \quad (\text{V}) \quad (13.73)$$

If the three-phase system has triangular arrangement with equidistant conductors such that $D_{AB} = D_{BC} = D_{AC} = D$, with the same radii for the conductors such that $r_A = r_B = r_C = r$ (where $D > r$), the expressions for V_{AB} and V_{AC} are

$$\begin{aligned} V_{AB} &= \frac{1}{2\pi\epsilon_0} \left[q_A \ln \left[\frac{D}{r} \right] + q_B \ln \left[\frac{r}{D} \right] + q_C \ln \left[\frac{D}{D} \right] \right] \\ &= \frac{1}{2\pi\epsilon_0} \left[q_A \ln \left[\frac{D}{r} \right] + q_B \ln \left[\frac{r}{D} \right] \right] \quad (\text{V}) \end{aligned} \quad (13.74)$$

$$\begin{aligned} V_{AC} &= \frac{1}{2\pi\epsilon_0} \left[q_A \ln \left[\frac{D}{r} \right] + q_B \ln \left[\frac{D}{D} \right] + q_C \ln \left[\frac{r}{D} \right] \right] \\ &= \frac{1}{2\pi\epsilon_0} \left[q_A \ln \left[\frac{D}{r} \right] + q_C \ln \left[\frac{r}{D} \right] \right] \quad (\text{V}) \end{aligned} \quad (13.75)$$

Balanced line-to-line voltages with sequence abc, expressed in terms of the line-to-neutral voltage are

$$V_{AB} = \sqrt{3} V_{AN} \angle 30^\circ \text{ and } V_{AC} = -V_{CA} = \sqrt{3} V_{AN} \angle -30^\circ;$$

where V_{AN} is the line-to-neutral voltage. Therefore, V_{AN} can be expressed in terms of V_{AB} and V_{AC} as

$$V_{AN} = \frac{V_{AB} + V_{AC}}{3} \quad (13.76)$$

and thus, substituting V_{AB} and V_{AC} from Eqs. (13.67) and (13.68) we have

$$\begin{aligned} V_{AN} &= \frac{1}{6\pi\epsilon_0} \left[\left[q_A \ln \left[\frac{D}{r} \right] + q_B \ln \left[\frac{r}{D} \right] \right] + \left[q_A \ln \left[\frac{D}{r} \right] + q_C \ln \left[\frac{r}{D} \right] \right] \right] \\ &= \frac{1}{6\pi\epsilon_0} \left[2q_A \ln \left[\frac{D}{r} \right] + (q_B + q_C) \ln \left[\frac{r}{D} \right] \right] \quad (\text{V}) \end{aligned} \quad (13.77)$$

Under balanced conditions $q_A + q_B + q_C = 0$, or $-q_A = (q_B + q_C)$ then, the final expression for the line-to-neutral voltage is

$$V_{AN} = \frac{1}{2\pi\epsilon_0} q_A \ln \left[\frac{D}{r} \right] \quad (\text{V}) \quad (13.78)$$

The positive sequence capacitance per unit length between phase A and neutral can now be obtained. The same result is obtained for capacitance between phases B and C to neutral

$$C_{AN} = \frac{q_A}{V_{AN}} = \frac{2\pi\epsilon_0}{\ln\left[\frac{D}{r}\right]} \text{ (F/m)} \quad (13.79)$$

13.5.4 Capacitance of Stranded Bundle Conductors

The calculation of the capacitance in the equation above is based on

1. Solid conductors with zero resistivity (zero internal electric field)
2. Charge uniformly distributed
3. Equilateral spacing of phase conductors

In actual transmission lines, the resistivity of the conductors produces a small internal electric field and therefore, the electric field at the conductor surface is smaller than the estimated. However, the difference is negligible for practical purposes.

Because of the presence of other charged conductors, the charge distribution is nonuniform, and therefore the estimated capacitance is different. However, this effect is negligible for most practical calculations. In a line with stranded conductors, the capacitance is evaluated assuming a solid conductor with the same radius as the outside radius of the stranded conductor. This produces a negligible difference.

Most transmission lines do not have equilateral spacing of phase conductors. This causes differences between the line-to-neutral capacitances of the three phases. However, transposing the phase conductors balances the system resulting in equal line-to-neutral capacitance for each phase and is developed in the following manner.

Consider a transposed three-phase line with conductors having the same radius r , and with space between conductors D_{AB} , D_{BC} , and D_{AC} , where D_{AB} , D_{BC} , and $D_{AC} > r$.

Assuming abc positive sequence, the expressions for V_{AB} on the first, second, and third section of the transposed line are

$$V_{AB \text{ first}} = \frac{1}{2\pi\epsilon_0} \left[q_A \ln \left[\frac{D_{AB}}{r} \right] + q_B \ln \left[\frac{r}{D_{AB}} \right] + q_C \ln \left[\frac{D_{AB}}{D_{AC}} \right] \right] \text{ (V)} \quad (13.80)$$

$$V_{AB \text{ second}} = \frac{1}{2\pi\epsilon_0} \left[q_A \ln \left[\frac{D_{BC}}{r} \right] + q_B \ln \left[\frac{r}{D_{BC}} \right] + q_C \ln \left[\frac{D_{AC}}{D_{AB}} \right] \right] \text{ (V)} \quad (13.81)$$

$$V_{AB \text{ third}} = \frac{1}{2\pi\epsilon_0} \left[q_A \ln \left[\frac{D_{AC}}{r} \right] + q_B \ln \left[\frac{r}{D_{AC}} \right] + q_C \ln \left[\frac{D_{AB}}{D_{BC}} \right] \right] \text{ (V)} \quad (13.82)$$

Similarly, the expressions for V_{AC} on the first, second, and third section of the transposed line are

$$V_{AC \text{ first}} = \frac{1}{2\pi\epsilon_0} \left[q_A \ln \left[\frac{D_{AC}}{r} \right] + q_B \ln \left[\frac{D_{BC}}{D_{AB}} \right] + q_C \ln \left[\frac{r}{D_{AC}} \right] \right] \quad (13.83)$$

$$V_{AC \text{ second}} = \frac{1}{2\pi\epsilon_0} \left[q_A \ln \left[\frac{D_{AB}}{r} \right] + q_B \ln \left[\frac{D_{AC}}{D_{BC}} \right] + q_C \ln \left[\frac{r}{D_{AB}} \right] \right] \quad (13.84)$$

$$V_{AC \text{ third}} = \frac{1}{2\pi\epsilon_0} \left[q_A \ln \left[\frac{D_{BC}}{r} \right] + q_B \ln \left[\frac{D_{AB}}{D_{AC}} \right] + q_C \ln \left[\frac{r}{D_{BC}} \right] \right] \quad (13.85)$$

Taking the average value of the three sections, we have the final expressions of V_{AB} and V_{AC} in the transposed line

$$V_{AB \text{ transp}} = \frac{V_{AB \text{ first}} + V_{AB \text{ second}} + V_{AB \text{ third}}}{3}$$

$$= \frac{1}{6\pi\epsilon_0} \left[q_A \ln \left[\frac{D_{AB}D_{AC}D_{BC}}{r^3} \right] + q_B \ln \left[\frac{r^3}{D_{AB}D_{AC}D_{BC}} \right] + q_C \ln \left[\frac{D_{AC}D_{AC}D_{BC}}{D_{AC}D_{AC}D_{BC}} \right] \right] \text{ (V)} \quad (13.86)$$

$$V_{AC \text{ transp}} = \frac{V_{AC \text{ first}} + V_{AC \text{ second}} + V_{AC \text{ third}}}{3}$$

$$= \frac{1}{6\pi\epsilon_0} \left[q_A \ln \left[\frac{D_{AB}D_{AC}D_{BC}}{r^3} \right] + q_B \ln \left[\frac{D_{AC}D_{AC}D_{BC}}{D_{AB}D_{AC}D_{BC}} \right] + q_C \ln \left[\frac{r^3}{D_{AC}D_{AC}D_{BC}} \right] \right] \text{ (V)} \quad (13.87)$$

For a balanced system where $-q_A = (q_B + q_C)$, the phase-to-neutral voltage V_{AN} (phase voltage) is

$$V_{AN \text{ transp}} = \frac{V_{AB \text{ transp}} + V_{AC \text{ transp}}}{3}$$

$$= \frac{1}{18\pi\epsilon_0} \left[2 q_A \ln \left[\frac{D_{AB}D_{AC}D_{BC}}{r^3} \right] + (q_B + q_C) \ln \left[\frac{r^3}{D_{AB}D_{AC}D_{BC}} \right] \right]$$

$$= \frac{1}{6\pi\epsilon_0} q_A \ln \left[\frac{D_{AB}D_{AC}D_{BC}}{r^3} \right] = \frac{1}{2\pi\epsilon_0} q_A \ln \left[\frac{\text{GMD}}{r} \right] \text{ (V)} \quad (13.88)$$

where $\text{GMD} = \sqrt[3]{D_{AB}D_{BC}D_{CA}}$ = geometrical mean distance for a three-phase line.

For bundle conductors, an equivalent radius r_e replaces the radius r of a single conductor and is determined by the number of conductors per bundle and the spacing of conductors. The expression of r_e is similar to $\text{GMR}_{\text{bundle}}$ used in the calculation of the inductance per phase, except that the actual outside radius of the conductor is used instead of the $\text{GMR}_{\text{phase}}$. Therefore, the expression for V_{AN} is

$$V_{AN \text{ transp}} = \frac{1}{2\pi\epsilon_0} q_A \ln \left[\frac{\text{GMD}}{r_e} \right] \text{ (V)} \quad (13.89)$$

where $r_e = (d^{n-1}r)^{1/n}$ = equivalent radius for up to three conductors per bundle (m)

$r_e = 1.09 (d^3 r)^{1/4}$ = equivalent radius for four conductors per bundle (m)

d = distance between bundle conductors (m)

n = number of conductors per bundle

Finally, the capacitance and capacitive reactance, per unit length, from phase to neutral can be evaluated as

$$C_{AN \text{ transp}} = \frac{q_A}{V_{AN \text{ transp}}} = \frac{2\pi\epsilon_0}{\ln \left[\frac{\text{GMD}}{r_e} \right]} \text{ (F/m)} \quad (13.90)$$

$$X_{AN \text{ transp}} = \frac{1}{2\pi f C_{AN \text{ transp}}} = \frac{1}{4\pi f \epsilon_0} \ln \left[\frac{\text{GMD}}{r_e} \right] \text{ (}\Omega/\text{m)} \quad (13.91)$$

13.5.5 Capacitance Due to Earth's Surface

Considering a single-overhead conductor with a return path through the earth, separated a distance H from earth's surface, the charge of the earth would be equal in magnitude to that on the conductor but of opposite sign. If the earth is assumed as a perfectly conductive horizontal plane with infinite length, then the electric field lines will go from the conductor to the earth, perpendicular to the earth's surface (Fig. 13.17).

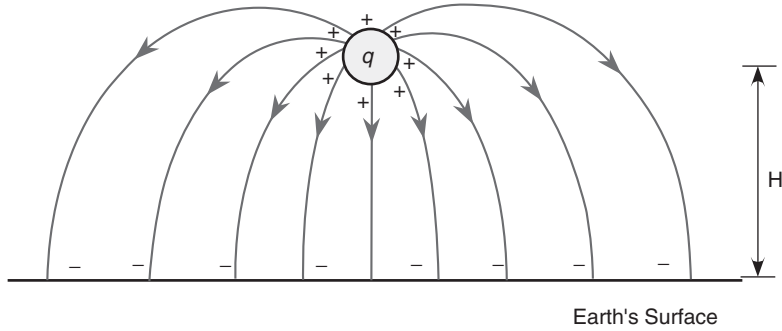


FIGURE 13.17 Distribution of electric field lines from an overhead conductor to earth's surface.

To calculate the capacitance, the negative charge of the earth can be replaced by an equivalent charge of an image conductor with the same radius as the overhead conductor, lying just below the overhead conductor (Fig. 13.18).

The same principle can be extended to calculate the capacitance per phase of a three-phase system. Figure 13.19 shows an equilateral arrangement of identical single conductors for phases A, B, and C carrying the charges q_A , q_B , and q_C and their respective image conductors A', B', and C'.

D_A , D_B , and D_C are perpendicular distances from phases A, B, and C to earth's surface. $D_{AA'}$, $D_{BB'}$, and $D_{CC'}$ are the perpendicular distances from phases A, B, and C to the image conductors A', B', and C'. Voltage V_{AB} can be obtained as

$$V_{AB} = \frac{1}{2\pi\epsilon_0} \left[q_A \ln \left[\frac{D_{AB}}{r_A} \right] + q_B \ln \left[\frac{r_B}{D_{AB}} \right] + q_C \ln \left[\frac{D_{BC}}{D_{AC}} \right] - \right. \\ \left. - q_A \ln \left[\frac{D_{AB'}}{D_{AA'}} \right] - q_B \ln \left[\frac{D_{BB'}}{D_{AB'}} \right] - q_C \ln \left[\frac{D_{BC'}}{D_{AC'}} \right] \right] \quad (\text{V}) \quad (13.92)$$

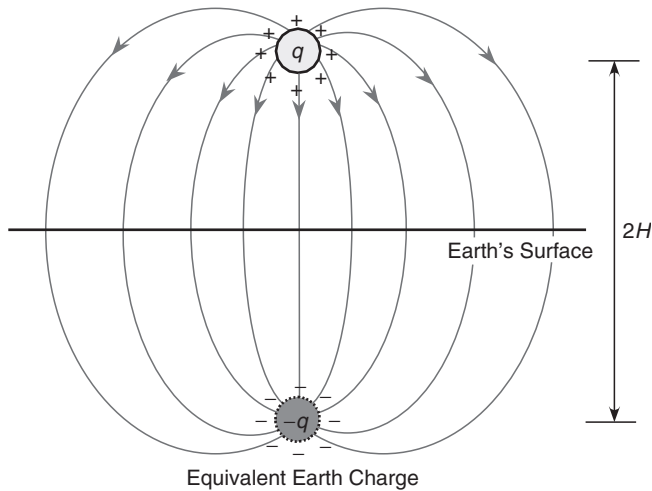


FIGURE 13.18 Equivalent image conductor representing the charge of the earth.

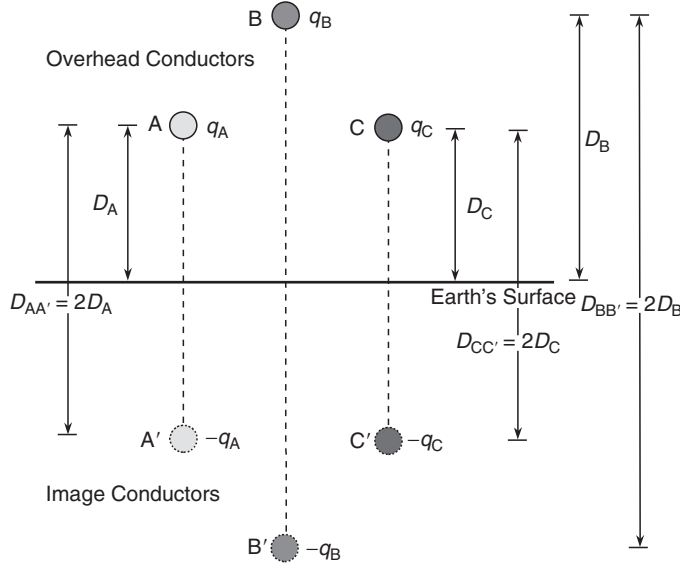


FIGURE 13.19 Arrangement of image conductors in a three-phase transmission line.

As overhead conductors are identical, then $r = r_A = r_B = r_C$. Also, as the conductors have equilateral arrangement, $D = D_{AB} = D_{BC} = D_{CA}$

$$V_{AB} = \frac{1}{2\pi\epsilon_0} \left[q_A \left(\ln \left[\frac{D}{r} \right] - \ln \left[\frac{D_{AB'}}{D_{AA'}} \right] \right) + q_B \left(\ln \left[\frac{r}{D} \right] - \ln \left[\frac{D_{BB'}}{D_{AB'}} \right] \right) - q_C \ln \left[\frac{D_{BC'}}{D_{AC'}} \right] \right] \quad (\text{V}) \quad (13.93)$$

Similarly, expressions for V_{BC} and V_{AC} are

$$V_{BC} = \frac{1}{2\pi\epsilon_0} \left[-q_A \ln \left[\frac{D_{CA'}}{D_{BA'}} \right] + q_B \left(\ln \left[\frac{D}{r} \right] - \ln \left[\frac{D_{CB'}}{D_{BB'}} \right] \right) + q_C \left(\ln \left[\frac{r}{D} \right] - \ln \left[\frac{D_{CC'}}{D_{BC'}} \right] \right) \right] \quad (\text{V}) \quad (13.94)$$

$$V_{AC} = \frac{1}{2\pi\epsilon_0} \left[q_A \left(\ln \left[\frac{D}{r} \right] - \ln \left[\frac{D_{CA'}}{D_{AA'}} \right] \right) - q_B \ln \left[\frac{D_{CB'}}{D_{AB'}} \right] + q_C \left(\ln \left[\frac{r}{D} \right] - \ln \left[\frac{D_{CC'}}{D_{AC'}} \right] \right) \right] \quad (\text{V}) \quad (13.95)$$

The phase voltage V_{AN} becomes, through algebraic reduction,

$$\begin{aligned} V_{AN} &= \frac{V_{AB} + V_{AC}}{3} \\ &= \frac{1}{2\pi\epsilon_0} q_A \left(\ln \left[\frac{D}{r} \right] - \ln \left[\frac{\sqrt[3]{D_{AB'} D_{BC'} D_{CA'}}}{\sqrt[3]{D_{AA'} D_{BB'} D_{CC'}}} \right] \right) \quad (\text{V}) \end{aligned} \quad (13.96)$$

Therefore, the phase capacitance C_{AN} , per unit length, is

$$C_{AN} = \frac{q_A}{V_{AN}} = \frac{2\pi\epsilon_0}{\ln \left[\frac{D}{r} \right] - \ln \left[\frac{\sqrt[3]{D_{AB'} D_{BC'} D_{CA'}}}{\sqrt[3]{D_{AA'} D_{BB'} D_{CC'}}} \right]} \quad (\text{F/m}) \quad (13.97)$$

Equations (13.79) and (13.97) have similar expressions, except for the term $\ln ((D_{AB'} D_{BC'} D_{CA'})^{1/3} / (D_{AA'} D_{BB'} D_{CC'})^{1/3})$ included in Eq. (13.97). That term represents the effect of the earth on phase capacitance, increasing its total value. However, the capacitance increment is really small, and is usually

TABLE 13.2a Characteristics of Aluminum Cable Steel Reinforced Conductors (ACSR)

Code	Cross-Section Area			Stranding Al/Steel	Diameter		Approx. Current- Carrying Capacity (Amperes)	Resistance (mΩ/km)				GMR (mm)	60 Hz Reactances (Dm = 1 m)		
	Total (mm ²)	Aluminum			Conductor (mm)	Core (mm)		Layers	DC 25°C	AC (60 Hz)			X ₁ (Ω/km)	X ₀ (MΩ/km)	
		(kcmil)	(mm ²)							25°C	50°C				75°C
—	1521	2 776	1407	84/19	50.80	13.87	4		21.0	24.5	26.2	28.1	20.33	0.294	0.175
Joree	1344	2 515	1274	76/19	47.75	10.80	4		22.7	26.0	28.0	30.0	18.93	0.299	0.178
Thrasher	1235	2 312	1171	76/19	45.77	10.34	4		24.7	27.7	30.0	32.2	18.14	0.302	0.180
Kiwi	1146	2 167	1098	72/7	44.07	8.81	4		26.4	29.4	31.9	34.2	17.37	0.306	0.182
Bluebird	1181	2 156	1092	84/19	44.75	12.19	4		26.5	29.0	31.4	33.8	17.92	0.303	0.181
Chukar	976	1 781	902	84/19	40.69	11.10	4		32.1	34.1	37.2	40.1	16.28	0.311	0.186
Falcon	908	1 590	806	54/19	39.24	13.08	3	1 380	35.9	37.4	40.8	44.3	15.91	0.312	0.187
Lapwing	862	1 590	806	45/7	38.20	9.95	3	1 370	36.7	38.7	42.1	45.6	15.15	0.316	0.189
Parrot	862	1 510	765	54/19	38.23	12.75	3	1 340	37.8	39.2	42.8	46.5	15.48	0.314	0.189
Nuthatch	818	1 510	765	45/7	37.21	9.30	3	1 340	38.7	40.5	44.2	47.9	14.78	0.318	0.190
Plover	817	1 431	725	54/19	37.21	12.42	3	1 300	39.9	41.2	45.1	48.9	15.06	0.316	0.190
Bobolink	775	1 431	725	45/7	36.25	9.07	3	1 300	35.1	42.6	46.4	50.3	14.39	0.320	0.191
Martin	772	1 351	685	54/19	36.17	12.07	3	1 250	42.3	43.5	47.5	51.6	14.63	0.319	0.191
Dipper	732	1 351	685	45/7	35.20	8.81	3	1 250	43.2	44.9	49.0	53.1	13.99	0.322	0.193
Pheasant	726	1 272	645	54/19	35.10	11.71	3	1 200	44.9	46.1	50.4	54.8	14.20	0.321	0.193
Bittern	689	1 272	644	45/7	34.16	8.53	3	1 200	45.9	47.5	51.9	56.3	13.56	0.324	0.194
Grackle	681	1 192	604	54/19	34.00	11.33	3	1 160	47.9	49.0	53.6	58.3	13.75	0.323	0.194
Bunting	646	1 193	604	45/7	33.07	8.28	3	1 160	48.9	50.4	55.1	59.9	13.14	0.327	0.196
Finch	636	1 114	564	54/19	32.84	10.95	3	1 110	51.3	52.3	57.3	62.3	13.29	0.326	0.196
Bluejay	603	1 113	564	45/7	31.95	8.00	3	1 110	52.4	53.8	58.9	64.0	12.68	0.329	0.197
Curlew	591	1 033	523	54/7	31.62	10.54	3	1 060	56.5	57.4	63.0	68.4	12.80	0.329	0.198

Ortolan	560	1 033	525	45/7	30.78	7.70	3	1 060	56.5	57.8	63.3	68.7	12.22	0.332	0.199
Merganser	596	954	483	30/7	31.70	13.60	2	1 010	61.3	61.8	67.9	73.9	13.11	0.327	0.198
Cardinal	546	954	483	54/7	30.38	10.13	3	1 010	61.2	62.0	68.0	74.0	12.31	0.332	0.200
Rail	517	954	483	45/7	29.59	7.39	3	1 010	61.2	62.4	68.3	74.3	11.73	0.335	0.201
Baldpate	562	900	456	30/7	30.78	13.21	2	960	65.0	65.5	71.8	78.2	12.71	0.329	0.199
Canary	515	900	456	54/7	29.51	9.83	3	970	64.8	65.5	72.0	78.3	11.95	0.334	0.201
Ruddy	478	900	456	45/7	28.73	7.19	3	970	64.8	66.0	72.3	78.6	11.40	0.337	0.202
Crane	501	875	443	54/7	29.11	9.70	3	950	66.7	67.5	74.0	80.5	11.80	0.335	0.202
Willet	474	874	443	45/7	28.32	7.09	3	950	66.7	67.9	74.3	80.9	11.25	0.338	0.203
Skimmer	479	795	403	30/7	29.00	12.40	2	940	73.5	74.0	81.2	88.4	11.95	0.334	0.202
Mallard	495	795	403	30/19	28.96	12.42	2	910	73.5	74.0	81.2	88.4	11.95	0.334	0.202
Drake	469	795	403	26/7	28.14	10.36	2	900	73.3	74.0	81.2	88.4	11.43	0.337	0.203
Condor	455	795	403	54/7	27.74	9.25	3	900	73.4	74.1	81.4	88.6	11.22	0.339	0.204
Cuckoo	455	795	403	24/7	27.74	9.25	2	900	73.4	74.1	81.4	88.5	11.16	0.339	0.204
Tern	431	795	403	45/7	27.00	6.76	3	900	73.4	74.4	81.6	88.8	10.73	0.342	0.205
Coot	414	795	403	36/1	26.42	3.78	3	910	73.0	74.4	81.5	88.6	10.27	0.345	0.206
Buteo	447	715	362	30/7	27.46	11.76	2	840	81.8	82.2	90.2	98.3	11.34	0.338	0.204
Redwing	445	715	362	30/19	27.46	11.76	2	840	81.8	82.2	90.2	98.3	11.34	0.338	0.204
Starling	422	716	363	26/7	26.7	9.82	2	840	81.5	82.1	90.1	98.1	10.82	0.341	0.206
Crow	409	715	362	54/7	26.31	8.76	3	840	81.5	82.2	90.2	98.2	10.67	0.342	0.206

Current capacity evaluated at 75°C conductor temperature, 25°C air temperature, wind speed of 1.4 mi/h, and frequency of 60 Hz.

Sources: *Transmission Line Reference Book 345 kV and Above*, 2nd ed., Electric Power Research Institute, Palo Alto, California, 1987. With permission.

Glover, J.D. and Sarma, M.S., *Power System Analysis and Design*, 3rd ed., Brooks/Cole, 2002. With permission.

TABLE 13.2b Characteristics of Aluminum Cable Steel Reinforced Conductors (ACSR)

Code	Cross-Section Area			Stranding Al/Steel	Diameter			Approx. Current- Carrying Capacity (Amperes)	Resistance (mΩ/km)				GMR (mm)	60 Hz Reactances (Dm = 1 m)	
	Total (mm ²)	Aluminum			Conductor (mm)	Core (mm)	Layers		DC 25°C	AC (60 Hz)				X ₁ (Ω/km)	X ₀ (MΩ/km)
		(kcmil)	(mm ²)							25°C	50°C	75°C			
Stilt	410	716	363	24/7	26.31	8.76	2	840	81.5	82.2	90.2	98.1	10.58	0.343	0.206
Grebe	388	716	363	45/7	25.63	6.4	3	840	81.5	82.5	90.4	98.4	10.18	0.346	0.208
Gannet	393	666	338	26/7	25.76	9.5	2	800	87.6	88.1	96.6	105.3	10.45	0.344	0.208
Gull	382	667	338	54/7	25.4	8.46	3	800	87.5	88.1	96.8	105.3	10.27	0.345	0.208
Flamingo	382	667	338	24/7	25.4	8.46	2	800	87.4	88.1	96.7	105.3	10.21	0.346	0.208
Scoter	397	636	322	30/7	25.88	11.1	2	800	91.9	92.3	101.4	110.4	10.70	0.342	0.207
Egret	396	636	322	30/19	25.88	11.1	2	780	91.9	92.3	101.4	110.4	10.70	0.342	0.207
Grosbeak	375	636	322	26/7	25.15	9.27	2	780	91.7	92.2	101.2	110.3	10.21	0.346	0.209
Goose	364	636	322	54/7	24.82	8.28	3	770	91.8	92.4	101.4	110.4	10.06	0.347	0.208
Rook	363	636	322	24/7	24.82	8.28	2	770	91.7	92.3	101.3	110.3	10.06	0.347	0.209
Kingbird	340	636	322	18/1	23.88	4.78	2	780	91.2	92.2	101.1	110.0	9.27	0.353	0.211
Swirl	331	636	322	36/1	23.62	3.38	3	780	91.3	92.4	101.3	110.3	9.20	0.353	0.212
Wood Duck	378	605	307	30/7	25.25	10.82	2	760	96.7	97.0	106.5	116.1	10.42	0.344	0.208
Teal	376	605	307	30/19	25.25	10.82	2	770	96.7	97.0	106.5	116.1	10.42	0.344	0.208
Squab	356	605	356	26/7	25.54	9.04	2	760	96.5	97.0	106.5	116.0	9.97	0.347	0.208
Peacock	346	605	307	24/7	24.21	8.08	2	760	96.4	97.0	106.4	115.9	9.72	0.349	0.210
Duck	347	606	307	54/7	24.21	8.08	3	750	96.3	97.0	106.3	115.8	9.81	0.349	0.210
Eagle	348	557	282	30/7	24.21	10.39	2	730	105.1	105.4	115.8	126.1	10.00	0.347	0.210
Dove	328	556	282	26/7	23.55	8.66	2	730	104.9	105.3	115.6	125.9	9.54	0.351	0.212
Parakeet	319	557	282	24/7	23.22	7.75	2	730	104.8	105.3	115.6	125.9	9.33	0.352	0.212

Osprey	298	556	282	18/1	22.33	4.47	2	740	104.4	105.2	115.4	125.7	8.66	0.358	0.214
Hen	298	477	242	30/7	22.43	9.6	2	670	122.6	122.9	134.9	147.0	9.27	0.353	0.214
Hawk	281	477	242	26/7	21.79	8.03	2	670	122.4	122.7	134.8	146.9	8.84	0.357	0.215
Flicker	273	477	273	24/7	21.49	7.16	2	670	122.2	122.7	134.7	146.8	8.63	0.358	0.216
Pelican	255	477	242	18/1	20.68	4.14	2	680	121.7	122.4	134.4	146.4	8.02	0.364	0.218
Lark	248	397	201	30/7	20.47	8.76	2	600	147.2	147.4	161.9	176.4	8.44	0.360	0.218
Ibis	234	397	201	26/7	19.89	7.32	2	590	146.9	147.2	161.7	176.1	8.08	0.363	0.220
Brant	228	398	201	24/7	19.61	6.53	2	590	146.7	147.1	161.6	176.1	7.89	0.365	0.221
Chickadee	213	397	201	18/1	18.87	3.78	2	590	146.1	146.7	161.0	175.4	7.32	0.371	0.222
Oriole	210	336	170	30/7	18.82	8.08	2	530	173.8	174.0	191.2	208.3	7.77	0.366	0.222
Linnet	198	336	170	26/7	18.29	6.73	2	530	173.6	173.8	190.9	208.1	7.41	0.370	0.224
Widgeon	193	336	170	24/7	18.03	6.02	2	530	173.4	173.7	190.8	207.9	7.25	0.371	0.225
Merlin	180	336	170	18/1	16.46	3.48	2	530	173.0	173.1	190.1	207.1	6.74	0.377	0.220
Piper	187	300	152	30/7	17.78	7.62	2	500	195.0	195.1	214.4	233.6	7.35	0.370	0.225
Ostrich	177	300	152	26/7	17.27	6.38	2	490	194.5	194.8	214.0	233.1	7.01	0.374	0.227
Gadwall	172	300	152	24/7	17.04	5.69	2	490	194.5	194.8	213.9	233.1	6.86	0.376	0.227
Phoebe	160	300	152	18/1	16.41	3.28	2	490	193.5	194.0	213.1	232.1	6.37	0.381	0.229
Junco	167	267	135	30/7	16.76	7.19	2	570	219.2	219.4	241.1	262.6	6.92	0.375	0.228
Partridge	157	267	135	26/7	16.31	5.99	2	460	218.6	218.9	240.5	262.0	6.61	0.378	0.229
Waxwing	143	267	135	18/1	15.47	3.1	2	460	217.8	218.1	239.7	261.1	6.00	0.386	0.232

Current capacity evaluated at 75°C conductor temperature, 25°C air temperature, wind speed of 1.4 mi/h, and frequency of 60 Hz.

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TABLE 13.3a Characteristics of All-Aluminum-Conductors (AAC)

Code	Cross-Section Area		Stranding	Diameter		Approx. Current-Carrying Capacity (Amperes)	Resistance (mΩ/km)				GMR (mm)	60 Hz Reactances (Dm = 1 m)	
	(mm ²)	kcmil or AWG		(mm)	Layers		DC 25°C	AC (60 Hz)		X _L (Ω/km)		X _C (MΩ/km)	
								25°C	50°C				75°C
Coreopsis	806.2	1591	61	36.93	4	1380	36.5	39.5	42.9	46.3	14.26	0.320	0.190
Galdioli	765.8	1511	61	35.99	4	1340	38.4	41.3	44.9	48.5	13.90	0.322	0.192
Carnation	725.4	1432	61	35.03	4	1300	40.5	43.3	47.1	50.9	13.53	0.324	0.193
Columbine	865.3	1352	61	34.04	4	1250	42.9	45.6	49.6	53.6	13.14	0.327	0.196
Narcissus	644.5	1272	61	33.02	4	1200	45.5	48.1	52.5	56.7	12.74	0.329	0.194
Hawthorn	604.1	1192	61	31.95	4	1160	48.7	51.0	55.6	60.3	12.34	0.331	0.197
Marigold	564.2	1113	61	30.89	4	1110	52.1	54.3	59.3	64.3	11.92	0.334	0.199
Larkspur	524	1034	61	29.77	4	1060	56.1	58.2	63.6	69.0	11.49	0.337	0.201
Bluebell	524.1	1034	37	29.71	3	1060	56.1	58.2	63.5	68.9	11.40	0.337	0.201
Goldenrod	483.7	955	61	28.6	4	1010	60.8	62.7	68.6	74.4	11.03	0.340	0.203
Magnolia	483.6	954	37	28.55	3	1010	60.8	62.7	68.6	74.5	10.97	0.340	0.203
Crocus	443.6	875	61	27.38	4	950	66.3	68.1	74.5	80.9	10.58	0.343	0.205
Anemone	443.5	875	37	27.36	3	950	66.3	68.1	74.5	80.9	10.49	0.344	0.205
Lilac	403.1	796	61	26.11	4	900	73.0	74.6	81.7	88.6	10.09	0.347	0.207
Arbutus	402.9	795	37	26.06	3	900	73.0	74.6	81.7	88.6	10.00	0.347	0.207
Nasturtium	362.5	715	61	24.76	4	840	81.2	82.6	90.5	98.4	9.57	0.351	0.209
Violet	362.8	716	37	24.74	3	840	81.1	82.5	90.4	98.3	9.48	0.351	0.209
Orchid	322.2	636	37	23.32	3	780	91.3	92.6	101.5	110.4	8.96	0.356	0.212
Mistletoe	281.8	556	37	21.79	3	730	104.4	105.5	115.8	126.0	8.38	0.361	0.215
Dahlia	281.8	556	19	21.72	2	730	104.4	105.5	115.8	125.9	8.23	0.362	0.216
Syringa	241.5	477	37	20.19	3	670	121.8	122.7	134.7	146.7	7.74	0.367	0.219
Cosmos	241.9	477	19	20.14	2	670	121.6	122.6	134.5	146.5	7.62	0.368	0.219
Canna	201.6	398	19	18.36	2	600	145.9	146.7	161.1	175.5	6.95	0.375	0.224
Tulip	170.6	337	19	16.92	2	530	172.5	173.2	190.1	207.1	6.40	0.381	0.228
Laurel	135.2	267	19	15.06	2	460	217.6	218.1	239.6	261.0	5.70	0.390	0.233
Daisy	135.3	267	7	14.88	1	460	217.5	218	239.4	260.8	5.39	0.394	0.233
Oxlip	107.3	212 or (4/0)	7	13.26	1	340	274.3	274.7	301.7	328.8	4.82	0.402	0.239
Phlox	85	168 or (3/0)	7	11.79	1	300	346.4	346.4	380.6	414.7	4.27	0.411	0.245
Aster	67.5	133 or (2/0)	7	10.52	1	270	436.1	439.5	479.4	522.5	3.81	0.40	0.25
Poppy	53.5	106 or (1/0)	7	9.35	1	230	550	550.2	604.5	658.8	3.38	0.429	0.256
Pansy	42.4	#1 AWG	7	8.33	1	200	694.2	694.2	763.2	831.6	3.02	0.438	0.261
Iris	33.6	#2 AWG	7	7.42	1	180	874.5	874.5	960.8	1047.9	2.68	0.446	0.267
Rose	21.1	#3 AWG	7	5.89	1	160	1391.5	1391.5	1528.9	1666.3	2.13	0.464	0.278
Peachbell	13.3	#4 AWG	7	4.67	1	140	2214.4	2214.4	2443.2	2652	1.71	0.481	0.289

Current capacity evaluated at 75°C conductor temperature, 25°C air temperature, wind speed of 1.4 mi/h, and frequency of 60 Hz.
Sources: *Transmission Line Reference Book 345 kV and Above*, 2nd ed., Electric Power Research Institute, Palo Alto, California, 1987. With permission.
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TABLE 13.3b Characteristics of All-Aluminum-Conductors (AAC)

Code	Cross-Section Area		Stranding	Diameter	Layers	Approx. Current-Carrying Capacity (Amperes)	Resistance (mΩ/km)				GMR (mm)	60 Hz Reactances (Dm = 1 m)	
	(mm ²)	kcmil or AWG		(mm)			25°C	AC (60 Hz)				X _L (Ω/km)	X _C (MΩ/km)
								25°C	50°C	75°C			
EVEN SIZES													
Bluebonnet	1773.3	3500	7	54.81	6		16.9	22.2	23.6	25.0	21.24	0.290	0.172
Trillium	1520.2	3000	127	50.75	6		19.7	24.6	26.2	27.9	19.69	0.296	0.175
Lupine	1266.0	2499	91	46.30	5		23.5	27.8	29.8	31.9	17.92	0.303	0.180
Cowslip	1012.7	1999	91	41.40	5		29.0	32.7	35.3	38.0	16.03	0.312	0.185
Jessamine	887.0	1750	61	38.74	4		33.2	36.5	39.5	42.5	14.94	0.317	0.188
Hawkweed	506.7	1000	37	29.24	3	1030	58.0	60.0	65.5	71.2	11.22	0.339	0.201
Camelia	506.4	999	61	29.26	4	1030	58.1	60.1	65.5	71.2	11.31	0.338	0.201
Snapdragon	456.3	900	61	27.79	4	970	64.4	66.3	72.5	78.7	10.73	0.342	0.204
Cockscomb	456.3	900	37	27.74	3	970	64.4	66.3	72.5	78.7	10.64	0.343	0.204
Cattail	380.1	750	61	25.35	4	870	77.4	78.9	86.4	93.9	9.78	0.349	0.208
Petunia	380.2	750	37	23.85	3	870	77.4	78.9	86.4	93.9	9.72	0.349	0.208
Flag	354.5	700	61	24.49	4	810	83.0	84.4	92.5	100.6	9.45	0.352	0.210
Verbena	354.5	700	37	24.43	3	810	83.0	84.4	92.5	100.6	9.39	0.352	0.210
Meadowsweet	303.8	600	37	2.63	3	740	96.8	98.0	107.5	117.0	8.69	0.358	0.214
Hyacinth	253.1	500	37	20.65	3	690	116.2	117.2	128.5	140.0	7.92	0.365	0.218
Zinnia	253.3	500	19	20.60	2	690	116.2	117.2	128.5	139.9	7.80	0.366	0.218
Goldentuft	228.0	450	19	19.53	2	640	129.0	129.9	142.6	155.3	7.41	0.370	0.221
Daffodil	177.3	350	19	17.25	2	580	165.9	166.6	183.0	199.3	6.52	0.379	0.227
Peony	152.1	300	19	15.98	2	490	193.4	194.0	213.1	232.1	6.04	0.385	0.230
Valerian	126.7	250	19	14.55	2	420	232.3	232.8	255.6	278.6	5.52	0.392	0.235
Sneezewort	126.7	250	7	14.40	1	420	232.2	232.7	255.6	278.4	5.21	0.396	0.235

Current capacity evaluated at 75°C conductor temperature, 25°C air temperature, wind speed of 1.4 mi/h, and frequency of 60 Hz.
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neglected, because distances from overhead conductors to ground are always greater than distances among conductors.

13.6 Characteristics of Overhead Conductors

Tables 13.2a and 13.2b present typical values of resistance, inductive reactance and capacitance reactance, per unit length, of ACSR conductors. The size of the conductors (cross-section area) is specified in square millimeters and kcmil, where a cmil is the cross-section area of a circular conductor with a diameter of 1/1000 in. The tables include also the approximate current-carrying capacity of the conductors assuming 60 Hz, wind speed of 1.4 mi/h, and conductor and air temperatures of 75°C and 25°C, respectively. Tables 13.3a and 13.3b present the corresponding characteristics of AACs.

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